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In general, very few fission yields have been measured on an absolute basis. In most cases, yields have been determined relative to Ba^{140} whose absolute yield has been averaged to 6.44% for U^{235} thermal fission. Where the reported data have been based on an assumed yield for Ba^{140} other than 6.44%, the values given in the tables have been re-normalized to 6.44%. Yields which have been determined relative to an isotope other than Ba^{140} are indicated by footnotes in the tables.

Table 1-2—CHARACTERISTICS OF PROMPT GAMMA RAYS EMITTED IN FISSION

Fissioning Isotope	Total Photons per Fission	Total Energy of Photons, Mev	Ref.
U^{235} + n	7.4	7.2	18
Cf^{252}	10.3	8.2	16

Fission Product Chains. The fission product radioactive chains are shown schematically in Table 1-3.

Total Chain Yields from U^{235}-Thermal Neutron Fission. Table 1-4 lists the total integrated chain yield for each mass number from thermal neutron fissions in U^{235}. The fission product given uniquely characterizes the total chain yield for the respective mass number. Where an actively decaying isotope is indicated, no other isotope further along the chain is formed directly in fission. By definition, the integrated chain yield is equivalent to the total fission yield of nuclei having a particular mass.

Direct Yield of Some Primary U^{235} Fission Products. Table 1-5 gives the yield directly at fission of some primary products from U^{235} fission induced by both thermal and 14-Mev neutrons. As is evident from Table 1-3, some of these primary-yield nuclei can also be formed as the result of beta decay in a chain. In such cases, they are product members of the chain and, hence, are not primary yields. The ratio of the number of particular nuclei formed directly at fission, to the total yield of nuclei having the same mass, is denoted as the direct yield fraction of the chain yield.

Cumulative Yields of Various Fission Products from Thermal Neutron Fission. The cumulative yield of a fission product is the probability that, in one fission, the fission product is formed either directly or later in the decay chain.

Table 1-6 lists the cumulative fission yields of various isotopes from thermal neutron fission of U^{233}, U^{235}, and Pu^{239}. The data in Table 1-4, which also represent cumulative yields, are not repeated.

The cumulative yields in Table 1-6 do not necessarily represent total chain yields since a later member of the chain may also be formed directly from fission. In addition, as a result of isomerism, the yields for some U^{235} fission products are lower than their counterparts listed in Table 1-4 for the total chain yield. In the absence of isomerism, any discrepancy between values for the same isotope in Tables 1-4 and 1-6 (for U^{235} fission) is due to experimental error. The values in Table 1-4 are considered more reliable.

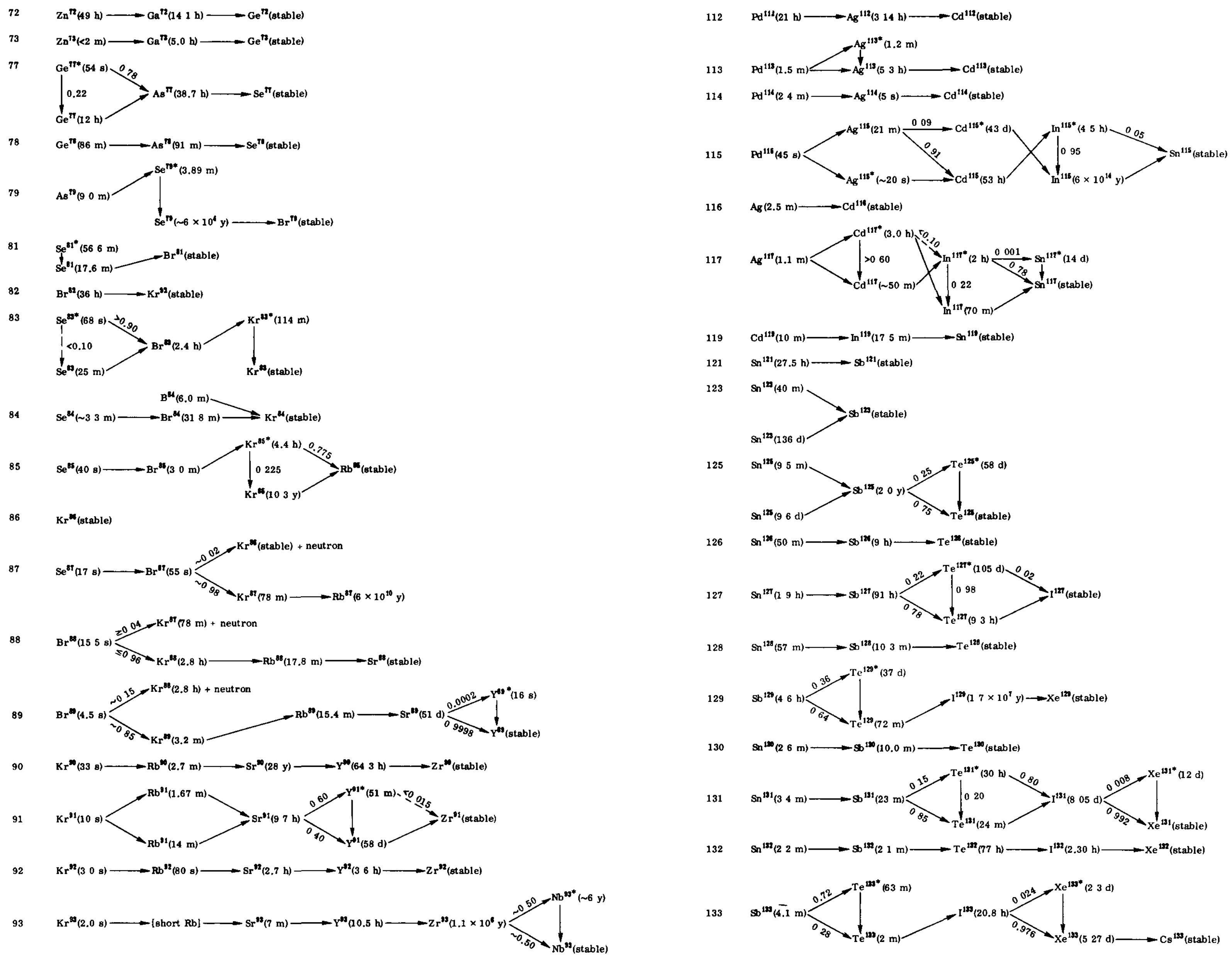
Cumulative Yields of Various Fission Products from Fast Fissions. The cumulative fission product yields from fission spectrum neutron-induced fissions in Pu^{239}, U^{238}, and Th^{232} are summarized in Table 1-7. Table 1-8 lists the yields from 14-Mev neutron-induced fissions in U^{235}, and 8-Mev neutron-induced fissions in Th^{232}.

The variation of yield for a given mass with incident energy for U^{235} fissions, shown in Fig. 1-2, is based on the data in Tables 1-4 and 1-8. The greatest change is the increase (by a factor of 100) in the probability of symmetric fission for 14-Mev neutrons. The peak yields drop slightly, but there is a small increase in the most asymmetric modes of fission.

1.2.4 FISSION FRAGMENT RANGES

The range of median-mass light and median-mass heavy fission fragments in representative materials is given in Figs. 1-3 and 1-4, respectively.[91] The residual energy after traversing the absorber was measured by a CsI(Tl) scintillator.

Table 1-3 — FISSION PRODUCT CHAINS



94 Kr^{94}(1 4 s) → [short Rb] → Sr^{94}(~2 m) → Y^{94}(16 5 m) → Zr^{94}(stable)

95 Y^{95}(10 5 m) → Zr^{95}(65 d) $\xrightarrow{0\ 02}$ Nb^{95*}(90 h) → Nb^{95}(35 d)
Zr^{95}(65 d) $\xrightarrow{0\ 98}$ Nb^{95}(35 d) → Mo^{95}(stable)

96 Nb^{96}(23 h) → Mo^{96}(stable)

96 Zr^{96}(stable)

97 Zr^{97}(17 0 h) → Nb^{97*}(60 s) → Nb^{97}(73 m)
Zr^{97}(17 0 h) $\xrightarrow{\leq 0\ 02}$ Nb^{97}(73 m) → Mo^{97}(stable)

98 Mo^{98}(stable)

99 Zr^{99}(30 s) → Nb^{99}(3 m) → Mo^{99}(66 h) $\xrightarrow{0\ 87}$ Tc^{99*}(6 0 h) → Tc^{99}(2 1 × 10^{5} y)
Mo^{99}(66 h) $\xrightarrow{0\ 13}$ Tc^{99}(2 1 × 10^{5} y) → Ru^{99}(stable)

100 Mo^{100}(stable)

101 Mo^{101}(14 6 m) → Tc^{101}(14 3 m) → Ru^{101}(stable)

102 Mo^{102}(11 5 m) → Tc^{102}(4 1 m) → Ru^{102}(stable)
Mo^{102}(11 5 m) → Tc^{102}(5 s) → Ru^{102}(stable)

103 Tc^{103}(1 2 m) → Ru^{103}(39 7 d) → Rh^{103*}(57 m)
Ru^{103}(39 7 d) $\xrightarrow{<0\ 05}$ Rh^{103}(stable)

104 [Mo^{104}(2 5 m)] → Tc^{104}(18 m) → Ru^{104}(stable)

105 [Mo^{105}(<2 m)] → Tc^{105}(10 m) → Ru^{105}(4 45 h) → Rh^{105*}(38 s) → Rh^{105}(35 3 h) → Pd^{105}(stable)

106 Ru^{106}(1 0 y) → Rh^{106}(30 s) → Pd^{106}(stable)

107 [Tc^{107}(<1 m)] → Ru^{107}(4 8 m) → Rh^{107*}(6 s) → Rh^{107}(22 m)
Ru^{107}(4 8 m) → Rh^{107}(22 m) → Pd^{107}(7 × 10^{6} y) → Ag^{107}(stable)

108 [Tc^{108}(<1 m)] → Ru^{108}(4 4 m) → Rh^{108}(18 s) → Pd^{108}(stable)

109 Pd^{109}(13 4 h) → Ag^{109*}(39 2 s) → Ag^{109}(stable)

111 SHORT [Rh^{111}] $\xrightarrow{\sim 0\ 01}$ Pd^{111*}(5 5 h) $\xrightarrow{0\ 75}$ Pd^{111}(23 m)
SHORT [Rh^{111}] $\xrightarrow{\sim 0\ 99}$ Pd^{111}(23 m) → Ag^{111}(7 6 d) → Cd^{111}(stable)
Pd^{111*}(5 5 h) ⇢ Ag^{111*}(74 s) → Ag^{111}(7 6 d)
Pd^{111*}(5 5 h) ⇢ Ag^{111}(7 6 d)
Pd^{111}(23 m) → Ag^{111*}(74 s)
Ag^{111*}(74 s) ⇢$^{<0\ 01}$ Cd^{111}(stable)

134 Sb^{134}(0 8 m) → Te^{134}(44 m) → I^{134}(52 5 m) → Xe^{134}(stable)

135 Te^{135}(<0 5 m) → I^{135}(6 7 h) $\xrightarrow{0\ 30}$ Xe^{135*}(15 3 m) → Xe^{135}(9 2 h)
I^{135}(6 7 h) $\xrightarrow{0\ 70}$ Xe^{135}(9 2 h) → Cs^{135}(2 6 × 10^{6} y) → Ba^{135}(stable)

136 Cs^{136}(13 d) → Ba^{136}(stable)

136 I^{136}(86 s) → Xe^{136}(stable)

137 I^{137}(24 0 s) $\xrightarrow{\sim 0\ 08}$ Xe^{136}(stable) + neutron
I^{137}(24 0 s) $\xrightarrow{\sim 0\ 92}$ Xe^{137}(3 9 m) → Cs^{137}(29 y) $\xrightarrow{0\ 92}$ Ba^{137*}(2 57 m) → Ba^{137}(stable)
Cs^{137}(29 y) $\xrightarrow{0\ 08}$ Ba^{137}(stable)

138 I^{138}(5 8 s) → Xe^{137} (3 9 m) + neutron
I^{138}(5 8 s) → Xe^{138}(17 m) → Cs^{138}(32 2 m) → Ba^{138}(stable)

139 I^{139}(2 7 s) → Xe^{139}(41 s) → Cs^{139}(9 5 m) → Ba^{139}(84 m) → La^{139}(stable)

140 Xe^{140}(16 s) → Cs^{140}(66 s) → Ba^{140}(12 8 d) → La^{140}(40 2 h) → Ce^{140}(stable)

141 Xe^{141}(1 7 s) → [short Cs] → Ba^{141}(18 m) → La^{141}(3 7 h) → Ce^{141}(33 d) → Pr^{141}(stable)

142 Ba^{142}(6 m) → La^{142}(75 m) → Ce^{142}(stable)

143 Xe^{143}(1 s) → [short Cs] → Ba^{143}(<0 5 m) → La^{143}(18 m) → Ce^{143}(33 h) → Pr^{143}(13 7 d) → Nd^{143}(stable)

144 Ce^{144}(285 d) → Pr^{144}(17 4 m) → Nd^{144}(5 × 10^{15} y)

145 Ce^{145}(3 0 m) → Pr^{145}(5 95 h) → Nd^{145}(stable)

146 Ce^{146}(13 9 m) → Pr^{146}(24 4 m) → Nd^{146}(stable)

147 Nd^{147}(11.1 d) → Pm^{147}(2 65 y) → Sm^{147}(1 3 × 10^{11} y)

148 Nd^{148}(stable)

148 Pm^{148}(5 3 d) → Sm^{148}(stable)

149 Nd^{149}(2 0 h) → Pm^{149}(54 h) → Sm^{149}(stable)

150 Nd^{150}(stable)

151 Nd^{151}(13 m) → Pm^{151}(27 5 h) → Sm^{151}(80 y) → Eu^{151}(stable)

152 Sm^{152}(stable)

153 Sm^{153}(47 h) → Eu^{153}(stable)

154 Sm^{154}(stable)

155 Sm^{155}(24 m) → Eu^{155}(1.9 y) → Gd^{155}(stable)

156 Sm^{156}(~10 h) → Eu^{156}(15 4 d) → Gd^{156}(stable)

157 Eu^{157}(15 4 h) → Gd^{157}(stable)

158 Eu^{158}(60 m) → Gd^{158}(stable)

159 Gd^{159}(18 0 h) → Tb^{159}(stable)

161 [Gd^{161}(3 6 m)] → Tb^{161}(6 9 d) → Dy^{161}(stable)

NOTE When branching occurs the fraction in each branch if known is indicated by the arrow. Dashed arrows are used when only the upper limits have been established Brackets denote that the given nuclide probably occurs in fission but that it has not been so observed

s = second m - minute h hour d - day y year * metastable

Table 1-4—TOTAL CHAIN YIELD FROM THERMAL NEUTRON FISSIONS IN U^{235}

s = second m = minute h = hour d = day y = year * = metastable

Mass No.	Fission Product	% Yield	Ref.	Mass No.	Fission Product	% Yield	Ref.
72	Zn^{72} (49h)	0.000016	20, 21	125	Sb^{125} (2.0y)	0.021	42
73	Ga^{73} (5.0h)	0.00011	21	126	Sb^{126} (9h)	0.05[a]	43
77	As^{77} (38.7h)	0.0083	22, 23	127	Sb^{127} (91h)	0.13[b]	37, 44
78	As^{78} (91m)	0.021	22	128	Sn^{128} (57m)	0.37	36
79	As^{79} (9.0m)	0.056	24	129	I^{129} (1.7×10^7y)	0.9	45
81	Se^{81} (17.6m)	0.14	25	130	Sb^{130} (10m)	2.0	46
83	Kr^{83} (stable)	0.544	26, 27, 28	131	Xe^{131} (stable)	2.93, 2.88[a]	28
84	Kr^{84} (stable)	1.00	26, 27, 28	132	Xe^{132} (stable)	4.38, 4.31[a]	28
85	Rb^{85} (stable)	1.30	26	133	Cs^{133} (stable)	6.59, 6.49[a]	26
86	Kr^{86} (stable)	2.02	26, 27, 28	134	Xe^{134} (stable)	8.06, 7.9[a]	28
87	Rb^{87} (6×10^{10}y)	2.49	26	135	Cs^{135} (2.6×10^6y)	6.41, 6.31[a]	26
88	Sr^{88} (stable)	3.57[b]	26, 29	136	Xe^{136} (stable)	6.46, 6.36[a]	28
89	Sr^{89} (51d)	4.79	30	137	Cs^{137} (29y)	6.15, 6.05[a]	28
90	Sr^{90} (28y)	5.77[b]	26, 29	138	Ba^{138} (stable)	5.74	29
91	Zr^{91} (stable)	5.84	29	139	Ba^{139} (84m)	6.55[b]	30, 47
92	Zr^{92} (stable)	6.03	29	140	Ce^{140} (stable)	6.44[b,c]	26, 29
93	Zr^{93} (1.1×10^6y)	6.45	29	141	Ce^{141} (33d)	~6.0	48
94	Zr^{94} (stable)	6.40	29	142	Ce^{142} (stable)	5.95	49
95	Mo^{95} (stable)	6.27	29	143	Nd^{143} (stable)	5.98[b]	26, 29
96	Zr^{96} (stable)	6.33	29	144	Nd^{144} (5×10^{15}y)	5.67[b]	26, 29
97	Mo^{97} (stable)	6.09	29	145	Nd^{145} (stable)	3.95[b]	26, 29
98	Mo^{98} (stable)	5.78	29	146	Nd^{146} (stable)	3.07[b]	26, 29
99	Mo^{99} (66h)	6.06[b]	30, 31	147	Sm^{147} (1.3×10^{11}y)	2.38	26
100	Mo^{100} (stable)	6.30	29	148	Nd^{148} (stable)	1.70[b]	26, 29
101	Ru^{101} (stable)	5.0	29	149	Sm^{149} (stable)	1.13	26
102	Ru^{102} (stable)	4.1	29	150	Nd^{150} (stable)	0.67[b]	26, 29
103	Ru^{103} (39.7d)	3.0	32, 33	151	Sm^{151} (80y)	0.45	26
104	Ru^{104} (stable)	1.8	29	152	Sm^{152} (stable)	0.285	26
105	Ru^{105} (4.45h)	0.90[b]	34, 35	153	Sm^{153} (47h)	0.15[b]	37, 49
106	Ru^{106} (1.01y)	0.38	29, 32, 33	154	Sm^{154} (stable)	0.077	26
107	Rh^{107} (22m)	0.19	36	155	Sm^{155} (24m)	0.033	50
109	Pd^{109} (13.4h)	0.030	37	156	Eu^{156} (15.4d)	0.014[b]	37, 49, 51
111	Ag^{111} (7.6d)	0.019	37	157	Eu^{157} (15.4h)	0.0078	52
112	Pd^{112} (21h)	0.010[b]	37, 38	158	Eu^{158} (60m)	0.002	52
115	Cd^{115} (53h) + Cd^{115*} (43d)	0.011	39	159	Gd^{159} (18h)	0.00107[a]	49, 53
117	Cd^{117*} (3.0h)	0.011	40	161	Tb^{161} (6.9d)	0.000076	49, 53
121	Sn^{121} (27.5h)	0.015	41				

[a]Average of values in references cited.
[b]E. P. Steinberg, ANL, Private Communication. Based on a yield of (6.15 + 5.94)/2 = 6.05 for Cs^{137}.
[c]Measured absolute yield is 6.32%. The number 6.44% is used to normalize other yields.

Table 1-5 — DIRECT YIELD OF PRIMARY FISSION PRODUCTS FROM THERMAL AND 14-MEV NEUTRON-INDUCED FISSIONS IN U-235

s = second m = minute h = hour d = day y = year * = metastable

Mass No.	Fission Product	Thermal Neutrons			14-Mev Neutrons		
		% Yield	Fraction of Chain Yield	Ref.	% Yield	Fraction of Chain Yield	Ref.
78	As^{78} (91m)	0.0019	9×10^{-2}	25			
82	Br^{82} (36h)	4×10^{-5}	1.2×10^{-4}[a]	31, 56	0.003	3×10^{-3}	54
86	Rb^{86} (19d)	3×10^{-5}	1.5×10^{-5}[a]	31, 57			
90	Y^{90} (6.4h)	<0.0013	$<2.3 \times 10^{-4}$	58			
91	Y^{91} (58d)	<0.05	$<9 \times 10^{-3}$	58			
96	Nb^{96} (23h)	5.7×10^{-4}	9×10^{-5}[a]	31, 59	0.0034	6.4×10^{-4}	54
102	Rh^{102} (210d)	$<5 \times 10^{-7}$	$<1.2 \times 10^{7}$	60			
131	Te^{131*} (30h)	<0.15	$<5 \times 10^{-2}$	61	1.6	0.35	55
131	Te^{131} (24m)	<0.09	$<3 \times 10^{-2}$	61	<1.4	<0.30	55
131	I^{131} (8.05d)	<0.03	$<1 \times 10^{-2}$	61	<0.36	$<8 \times 10^{-2}$	55
132	I^{132} (2.3h)	<0.044	$<1 \times 10^{-2}$	61	0.8	0.16	55
133	Te^{133} (2m)	<0.66	<0.1	61	<2.2	<0.40	55
133	I^{133} (20.8h)	<0.33	$<5 \times 10^{-2}$	61	<2.2	<0.40	55
133	Xe^{133} (5.27d)	<0.0066	$<1 \times 10^{-3}$	62			
134	I^{134} (52.5m)	0.89	0.11	61	2.5	0.43	55
135	Xe^{135} (9.2h)	0.19	0.03	62, 63			
136	Xe^{136} (stable)	3.4	0.53	64			
136	Cs^{136} (13d)	0.006	9×10^{-4}[a]	31, 57	0.22	4×10^{-2}	54
140	La^{140} (40.2h)	<0.2	$<3 \times 10^{-2}$	65			
141	La^{141} (3.7h)	~0.1	$\sim 2 \times 10^{-2}$	66			
148	Pm^{148} (5.3d)	$<2 \times 10^{-4}$	$<1 \times 10^{-4}$	31			

[a]Average of values in references cited.

Table 1-6 — CUMULATIVE YIELDS OF VARIOUS FISSION PRODUCTS FROM THERMAL NEUTRON FISSIONS IN U^{233}, U^{235}, AND Pu^{239}

s = second m = minute h = hour d = day y = year * = metastable

Mass No.	Fission Product	U^{233} % Yield	U^{233} Ref.	U^{235} % Yield	U^{235} Ref.	Pu^{239} % Yield[a,b,c]	Mass No.	Fission Product	U^{233} % Yield	U^{233} Ref.	U^{235} % Yield	U^{235} Ref.	Pu^{239} % Yield[a,b,c]
72	Zn^{72} (49h)					0.00012	127	Sb^{127} (91h)					0.39
77	Ge^{77} (12h)	0.010	31	0.0031[d]	22, 23		127	Te^{127*} (105d)			0.035	67	
77	As^{77} (38.7h)	0.019	31				129	Te^{129*} (37d)			0.35	44	
78	Ge^{78} (86m)			0.020[d]	22, 23		131	Sb^{131} (23m)			2.6	46	
81	Se^{81*} (57m)			0.0084	25		131	Te^{131*} (30h)			0.44	44	
83	Se^{83} (25m)			0.22	56		131	I^{131} (8.05d)	2.7	31	3.1[a]	37, 68	3.8
83	Br^{83} (2.4h)	0.79	31	0.51	57	0.085	131	Xe^{131} (stable)	3.74	67			2.87
83	Kr^{83} (stable)	1.14	67				132	Te^{132} (77h)			4.7	44	5.2
84	Br^{84} (31.8m)			0.90	58		132	Xe^{132} (stable)	5.10	67			4.02
84	Kr^{84} (stable)	1.90	67				133	Sb^{133} (4.1m)			4.0	44	
85	Kr^{85} (10.3y)	0.56	67	0.293[d]	26, 27, 28		133	Te^{133*} (63m)			4.9	44	
86	Kr^{86} (stable)	3.18	67				133	I^{133} (21h)			6.9	44	5.3
87	Br^{87} (55s)			3.1	59		133	Xe^{133} (5.27d)			6.62	69	5.27
89	Sr^{89} (51d)	6.5	31			1.9	133	Cs^{133} (stable)	6.18	67			5.27
90	Sr^{90} (28y)			5.8[d]	26, 29, 60, 61		134	Te^{134} (44m)			6.9[a]	44, 70	
91	Sr^{91} (9.7h)			5.8[d]	29, 60, 61	2.4	134	Xe^{134} (stable)	6.54	67			5.69
91	Sr^{91} (2.7h)			5.3	62		135	I^{135} (6.7h)	5.1	31	6.1[a]	44, 71, 72	5.8
91	Y^{91} (58d)			5.35	60	3.0	135	Cs^{135} (2.6×10^6y)	>4.9	67			5.53
91	Zr^{91} (stable)	6.53	68				136	I^{136} (86s)	1.7	64	3.1	73	2.1
92	Zr^{92} (stable)	6.70	68				136	Xe^{136} (stable)	<8.9	67			5.06
93	Zr^{93} (1.1×10^6y)	7.10	68				137	Cs^{137} (29y)	7.16	31	6.15	26, 74	5.24
94	Y^{94} (16.5m)			5.4	63		138	Cs^{138} (32m)			5.74	29, 75	
94	Zr^{94} (stable)	6.82	68				139	Ba^{139} (84m)					5.7
95	Zr^{95} (65d)	5.9	31	6.2	64	5.9	140	Ba^{140} (12.8d)	6.0	31	6.44[e]	29, 30, 70	5.68
95	Mo^{95} (stable)	6.10	68				140	Ce^{140} (stable)	5.6	69			5.68

96	Zr^{96} (stable)	5.60	68				141	Ce^{141} (33d)					5.2
97	Zr^{97} (17h)			5.9[d]	30, 64	5.7	142	Ce^{142} (stable)	5.6	69			6.69
97	Mo^{97} (stable)	5.35	68				143	Ce^{143} (33h)			5.7	26, 29, 77	5.4
98	Mo^{98} (stable)	5.18	68				143	Nd^{143} (stable)	5.2	69, 70			6.31
99	Mo^{99} (66h)	4.8	31			5.9	144	Ce^{144} (285d)	4.1	69, 70	6.0	26, 29	5.28
100	Mo^{100} (stable)	4.40	68				144	Nd^{144} (stable)	4.0	69, 70			5.29
101	Mo^{101} (14.6m)			~5.6	35		145	Nd^{145} (stable)	3.0	69, 70			4.24
101	Ru^{101} (stable)	3.00	68				146	Nd^{146} (stable)	2.3	69, 70			3.53
102	Mo^{102} (11.5m)			4.3	35		147	Nd^{147} (11d)			2.7	26, 78	
102	Ru^{102} (stable)	2.37	68				147	Sm^{147} (stable)	1.71	70			2.92
103	Ru^{103} (39.7d)	1.6	31			5.8	148	Nd^{148} (stable)	1.15	69, 70			2.28
104	Ru^{104} (stable)	0.96	68				149	Pm^{149} (5.6h)			1.4	26, 78	
105	Rh^{105} (35.3h)					3.9	149	Sm^{149} (stable)	0.61	70			1.89
106	Ru^{106} (1.01y)	0.28	31			5.0	150	Nd^{150} (stable)	0.48	69, 70			1.38
109	Pd^{109} (13.4h)	0.040	31	0.030	37	1.5	151	Sm^{151} (80y)	0.27	70			1.17
111	Ag^{111} (7.6d)	0.025	31			0.27	152	Sm^{152} (stable)	0.17	70			0.83
112	Pd^{112} (21h)	0.016	31			0.10	153	Sm^{153} (47h)	0.095	31			0.41
115	Ag^{115} (21m)			0.0077	39		154	Sm^{154} (stable)	0.037	70			0.32
115	Cd^{115*} (43d)	0.001	31	0.0007	39	0.003	155	Sm^{155} (24m)					0.22
115	Cd^{115} (53h)	0.019	31	0.0097	39	0.038	155	Eu^{155} (1.9y)			0.03	50, 51	
121	Sn^{121} (27.5h)	0.018	31			0.044	156	Sm^{156} (10h)			0.013	38, 49, 51	
123	Sn^{123} (136d)			0.0013	65		156	Eu^{156} (15.4h)					0.12
125	Sn^{125} (9.6d)	0.050	31	0.013	66	0.072							

[a] The Cs, Nd, and Sm yields were measured by Wiles, et al.,[79] and corrected to 5.6% yield for Ba^{140}. For some of the Ce and Nd isotopes, the ratios of yields per Ref. 80 were used.

[b] Most values are from Ref. 81, corrected to a Ba^{140} yield of $1.06 \times 5.32\% = 5.68\%$.

[c] The xenon isotope yields were determined by Fleming, et al.[82] These were normalized to corrected Cs yields at mass 133.

[d] Average of values in references cited.

[e] Measured value is 6.32%. The factor 1.06 is introduced to bring the total yield for light and heavy groups to 100% each.

Table 1-7 — CUMULATIVE PERCENTAGE YIELDS FROM FISSION SPECTRUM NEUTRON-INDUCED FISSIONS IN Pu^{239}, U^{238}, AND Th^{232}

s = second m = minute h = hour d = day y = year * = metastable

Mass No.	Fission Product	Pu^{239}[a]	U^{238}[b]	Th^{232}[c]	Mass No.	Fission Product	Pu^{239}[a]	U^{238}[b]	Th^{232}[c]
72	Zn^{72} (49h)			0.00033	111	Ag^{111} (7.6d)		0.073	0.052
73	Ga^{73} (5.0h)			0.00045	112	Pd^{112} (21h)	0.14	0.046	0.057
77	Ge^{77} (12h)			0.009	115	Cd^{115*} (43d)		0.003	0.003
77	As^{77} (39h)		0.0038	0.020	115	Cd^{115} (53h)	0.069	0.037	0.072
83	Br^{83} (2.4h)			1.9	127	Sb^{127} (93h)		0.12	
83	Kr^{83} (stable)		0.40	1.99	131	I^{131} (8.05d)			1.2
84	Kr^{84} (stable)		0.85	3.65	131	Xe^{131} (stable)		3.2[d]	1.62
85	Kr^{85} (10.3y)		0.153	0.87	132	Te^{132} (77h)		4.7	2.4
86	Kr^{86} (stable)		1.38	6.0	132	Xe^{132} (stable)		4.7[d]	2.87
89	Sr^{89} (51d)		2.9	6.7	133	Cs^{133} (stable)		5.5 (8.08)[e]	
90	Sr^{90} (28y)	2.2	3.2	6.8	134	Xe^{134} (stable)		6.6[d]	5.38
91	Sr^{91} (9.7h)			7.2	135	Cs^{135} (2.6×10^6y)		6.0[e]	
95	Zr^{95} (65d)		5.7		136	Xe^{136} (stable)		5.9[d]	5.65
97	Zr^{97} (17h)	5.2		5.2	137	Cs^{137} (29y)	6.6	6.2 (7.11)[e]	6.3
99	Mo^{99} (67h)	5.9	6.3	2.7	140	Ba^{140} (12.8d)	5.0	5.7	6.2
103	Ru^{103} (40d)		6.6	0.16	141	Ce^{141} (33d)			9.0
105	Rh^{105} (35h)			0.07	144	Ce^{144} (290d)		4.9	7.1
106	Ru^{106} (1.0y)		2.7	0.042	153	Sm^{153} (47h)	0.48		
109	Pd^{109} (13.4h)	1.9	0.32	0.055	156	Eu^{156} (15.4d)		0.066	

[a] Values from Ref. 83.
[b] Most values are averages of data in Refs. 84 and 85 normalized to absolute yield of Mo^{99} in Ref. 86.
[c] Most values from Ref. 87. Kr and Xe yields measured by T. J. Kennett and H. G. Thode, and reported by private communication to S. Katcoff.
[d] Values from Ref. 88.
[e] Cs^{133} and Cs^{135} yields derived from ratios to Cs^{137} measured by R. H. Tomlinson and reported by private communication to S. Katcoff.

Table 1-8 — CUMULATIVE PERCENTAGE YIELDS FROM 14-MEV NEUTRON-INDUCED FISSIONS IN U^{235} AND 8-MEV NEUTRON-INDUCED FISSIONS IN Th^{232}

s = second m = minute h = hour d = day y = year * = metastable

Mass No.	Fission Product	Cumulative % Yield in		Mass No.	Fission Product	Cumulative % Yield in	
		U^{235}	Th^{232}			U^{235}	Th^{232}
77	Ge^{77} (12h)		0.022	131	I^{131} (8.05d)	4.3	
83	Br^{83} (2.4h)	1.30		132	Te^{132} (77h)	4.3	2.0
83	Kr^{83} (stable)		2.7	132	I^{132} (2.3h)	5.0	
89	Sr^{89} (51d)	4.38	6.7	133	I^{133} (20.8h)	5.4	
91	Sr^{91} (9.7h)	4.19	5.6	133	Cs^{133} (stable)	5.6	
97	Zr^{97} (17h)	4.87	5.0	134	I^{134} (52.5m)	5.3	
99	Mo^{99} (66h)	5.17	3.1	134	Xe^{134} (stable)	5.9	
103	Ru^{103} (39.9d)	3.31	0.5	135	I^{135} (6.7h)	4.5	
105	Rh^{105} (35.3h)	1.86		135	Cs^{135} (2.6×10^6y)	5.7	
106	Ru^{106} (1.01y)	1.41	0.53	139	Ba^{139} (84m)	4.87	9.0
111	Ag^{111} (7.6d)	0.92	0.63	140	Ba^{140} (12.8d)	4.58	
115	Cd^{115} (53h)	0.89	0.76	143	Ce^{143} (33h)	3.72	
115	$Total^{115}$ chain	0.94		144	Ce^{144} (285d)	2.75	7.2
117	Cd^{117*} (3.0h)		0.4	156	Eu^{156} (15.4d)	0.11	
127	Sb^{127} (91h)	1.9					

Note: Most of the data by Ford and Gilmore,[89] and Turkevich, et al.[90] Iodine data by Wahl.[55] All values normalized to Mo^{99} as reported by Terrell.[86]

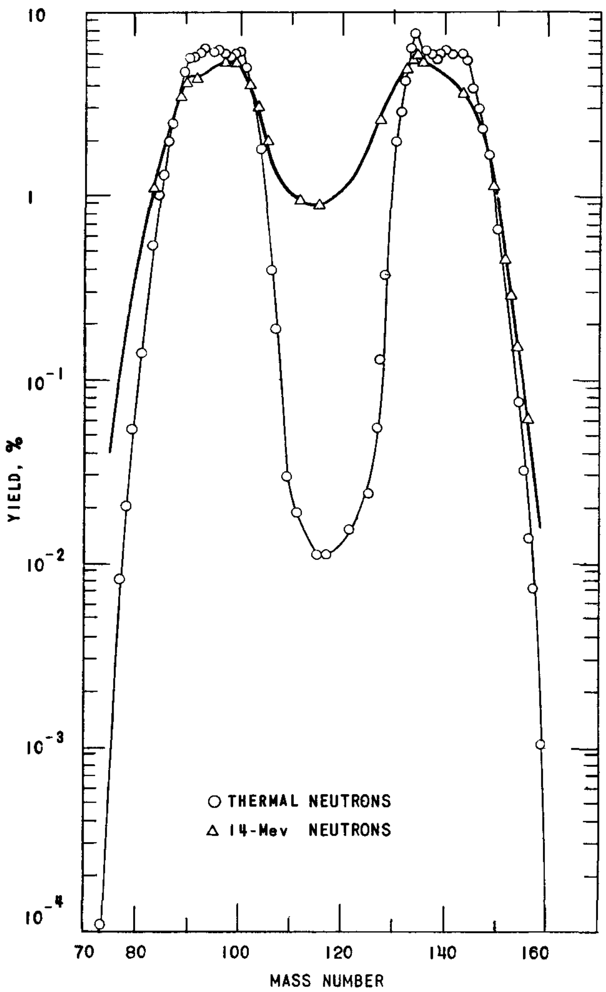


Fig. 1-2—Yield vs mass number for U^{235} fissions as a function of incident neutron energy.

1.3 PROMPT FISSION NEUTRON ENERGY SPECTRUM

Approximately 99% of the fission neutrons emitted at or immediately after fission ($\lesssim 10^{-10}$ sec) are defined as "prompt."[16,92,93] Most of these prompt neutrons are emitted isotropically from the moving fragment.[16,94] As a result, there is a correlation between the directions of the fragment and emitted neutron. The energy distribution of the prompt neutrons is described analytically by:[95,96]

$$N(E) = a\sqrt{E}\,e^{-E/T}$$

where E is the neutron energy in Mev; N(E) is the number of neutrons per unit energy interval; a is a constant dependent on the average number of neutrons emitted per fission; and T is a constant characteristic of the individual process.

1.3.1 EXPERIMENTAL DETERMINATIONS OF PROMPT FISSION NEUTRON SPECTRA

Experimental studies of prompt fission neutron spectra have been carried out by a number of workers.[97–109] Typical results of the measurement of $U^{235} + n_{th}$, $Pu^{239} + n_{th}$, and Cf^{252} spontaneous fission neutron spectra are shown in Figs. 1-5, 1-6, and 1-7, respectively. The average fission neutron energies obtained from Maxwellian spectral fits to existing measurements are summarized in

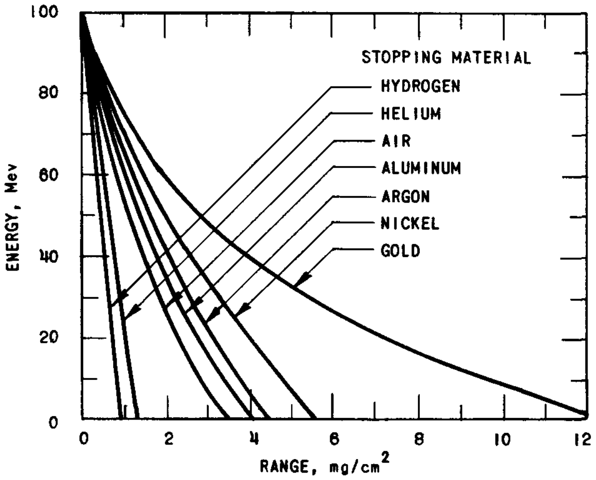


Fig. 1-3—Energy of median-mass light fission fragments of U^{235} (magnetically selected) as a function of range in various materials. *Reproduced from Ref. 91.*

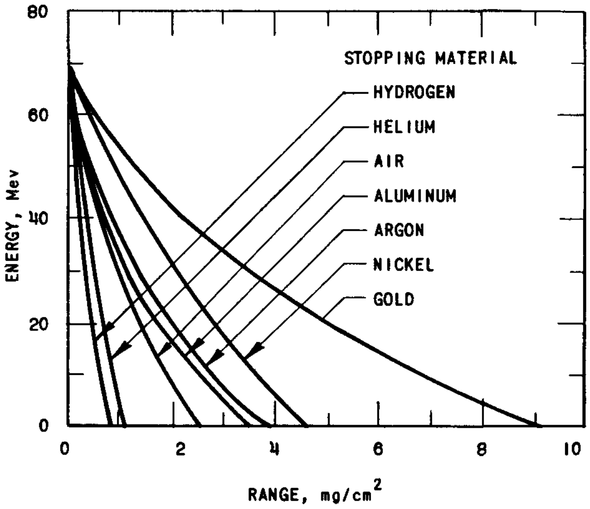


Fig. 1-4—Energy of median-mass heavy fission fragments of U^{235} (magnetically selected) as a function of range in various materials. *Reproduced from Ref. 91.*

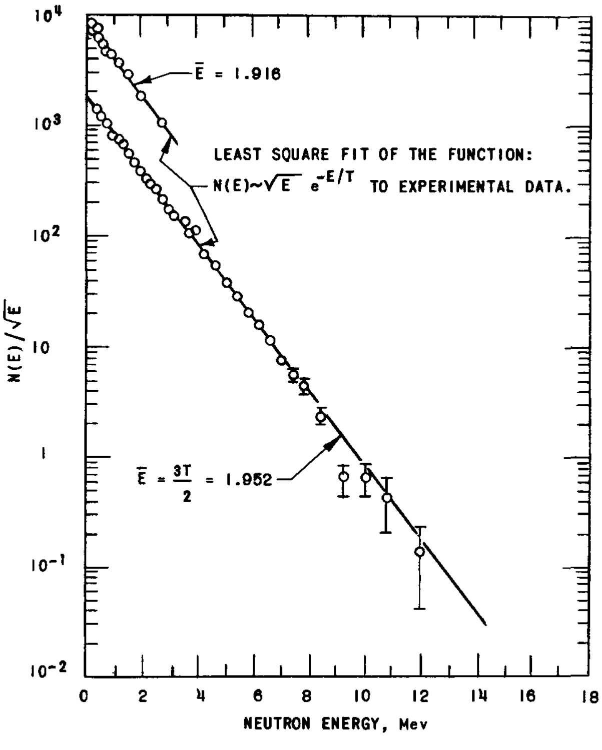


Fig. 1-5—Experimental determination of the fission neutron spectrum of $U^{235} + n_{th}$. *Reproduced from Ref. 97.*

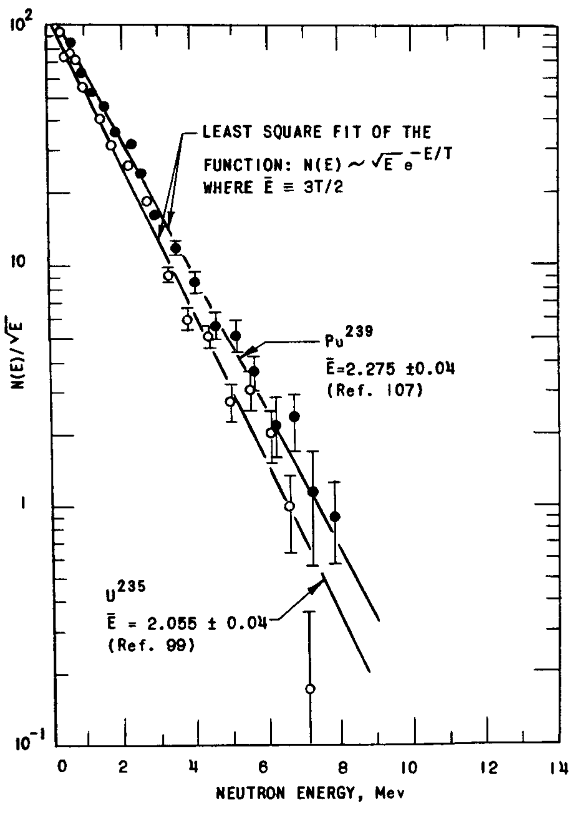


Fig. 1-6—Typical measured fission neutron spectra of $U^{235} + n_{th}$ and $Pu^{239} + n_{th}$. *Reproduced from Refs. 99 and 107.*

Table 1-9. Utilizing the relation $\bar{E} = 3T/2$ and the $\bar{\nu}$ values given in Section 1.5, the prompt fission neutron spectrum of each fission process can be generated. Average values of these necessary parameters for thermal neutron-induced fission processes are given in Table 1-10. The Maxwellian spectrum can be extrapolated to non-thermal incident neutron energies and to unmeasured neutron spectrum by utilizing the expression:[95]

$$\bar{E} = 0.78 + 0.621\sqrt{\bar{\nu} + 1}$$

Suitable $\bar{\nu}$ values are given in Section 1.5. Qualitatively, the isotropy and incident neutron energy dependence of the prompt fission spectrum are small.

Table 1-9 — AVERAGE ENERGY OF FISSION SPECTRUM NEUTRONS

Fissioning Nuclide	Energy Range, Mev	Method	$\bar{E}$, Mev[a] (Maxwellian)	$\bar{E}^b$, Mev	Ref.
$U^{235} + n_{th}$	0.35–12	Time of flight	1.916 ± 0.04	1.935 ± 0.05	97
	0.18–3	Photoplate	1.952 ± 0.013		97
	1.0–12	Photoplate	1.91 ± 0.04		98
	0.4–7	Photoplate	2.055 ± 0.04		99
	3.3–17	Prop. counter	1.854 ± 0.01		101
$U^{233} + n_{th}$	2.7	Threshold det.	$\bar{E}(U^{235})$ + 0.02 ± 0.01		103
	1.3–11	Prop. counter	2.17 ± 0.10		104
	2.0–8	Photoplate	2.23 ± 0.13		
	0.3–9	Time of flight and photoplate	1.87 ± 0.04	1.93 ± 0.06	106
	2.7	Threshold det.	$\bar{E}(U^{235})$ + 0.06 ± 0.02		105
	1.0–10	Photoplate	2.04 ± 0.06		98
$Pu^{239} + n_{th}$	2.7	Threshold det.	$\bar{E}(U^{235})$ + 0.07 ± 0.02	2.00 ± 0.05	103
	2.7	Threshold det.	$\bar{E}(U^{235})$ + 0.08 ± 0.02		105
	1.0–12	Photoplate	1.87 ± 0.05		98
	0.6–8	Photoplate	2.275 ± 0.04		107
Cf^{252} Spontaneous	2.0–10	Photoplate	2.12 ± 0.24	2.20 ± 0.1	108
	1.4–7	Photoplate	2.35 ± 0.08		109
	0.3–4	Time of flight	2.13 ± 0.05		

[a]Average energy given by least-squares fit to Maxwellian spectrum; the uncertainties are based on the standard deviations of the data points and do not include possible systematic errors in the energy scale.

[b]Average energy (arbitrarily weighted); uncertainties are over-all standard deviations.

1.3.2 THE $U^{235} + n_{th}$ PROMPT FISSION NEUTRON SPECTRUM AS A FUNCTION OF THE LETHARGY, u*

In some applications it is convenient to express the fission spectrum, F(u), in terms of the lethargy u. For u = ln (10/E):

$$F(u) = f(10\ e^{-u}) \left|\frac{dE}{du}\right|$$

and satisfies the normalization condition:

$$\int_{-\infty}^{\infty} F(u)\ du = 1$$

*Throughout the lethargy calculations, the average fission neutron energy, $\bar{E}$, is accepted as 1.98 Mev.

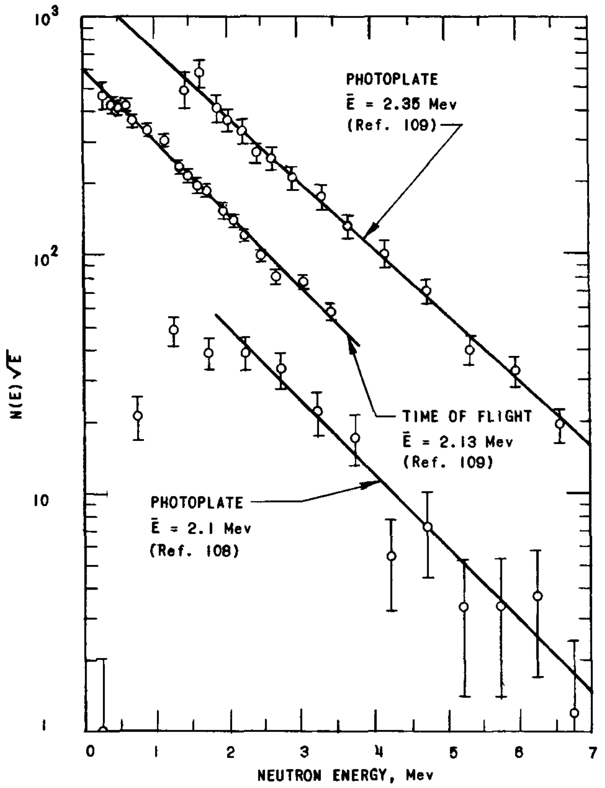


Fig. 1-7 — Least-squares fit of the spectral distribution $N(E) \sim \sqrt{E}\ \exp\ (-E/T)$ to the measured fission spectrum of Cf^{252}. *Reproduced from Refs. 108 and 109.*

Table 1-10 — PARAMETERS FOR THE PROMPT FISSION NEUTRON SPECTRUM

$$N(E) = a\sqrt{E}\ e^{-E/T}$$

Isotope	a	$T = \frac{2}{3}\bar{E}$
$U^{235} + n_{th}$	1.872	1.290
$U^{233} + n_{th}$	1.888	1.306
$Pu^{239} + n_{th}$	2.121	1.333
Cf^{252}	2.410	1.466

The integral of F(u),

$$I_F(u) = \int_{-\infty}^{u} F(x)\ dx = \int_{E}^{\infty} f(x)\ dx = I_f(E)$$

where E is the energy value corresponding to a given u.

Table 1-11 lists the values of u, f(E), and $I_f(E)$ for $0.05 \leq E \leq 20$ in intervals $\Delta E = 0.05$ for $0.05 \leq E \leq 6.0$, and in intervals $\Delta E = 1$ for $6 \leq E \leq 20$.

Table 1-12 lists the values of E, F(u), and $I_F(u)$ for $-0.7 \leq u \leq 20$ in intervals $\Delta u = 0.1$.

1.4 DELAYED FISSION NEUTRON EMISSION

Very soon after the discovery of fission neutron emission it was suggested,[110] and experimentally verified,[111] that ~1% of the fission neutrons was emitted long after the actual splitting of the parent nucleus. The importance of these delayed neutrons is out of proportion to their relatively small abundance due to the part they play in the control of multiplying systems. In this review, delayed neutrons are defined as those neutrons emitted an average time of $\gtrsim 10^{-3}$ seconds after the actual scission. Delayed neutron emission from U^{235}, U^{233}, U^{238}, Pu^{239}, Pu^{240}, and Th^{232} fission is described in terms of six exponentially decaying neutron groups. These groups are characterized by a half-life, T_i; a decay constant, λ_i; and a relative abundance, a_i. It is recognized that this six-group description of delayed neutron emission is a simplification of a very complex phenomena deeply rooted in the stability properties of neutron-rich nuclei. However, the six-group picture employed in the following is believed to be satisfactory for reactor design work.

Table 7-6 — OBSERVED CRITICAL MASSES: HIGH-DENSITY SPHERICAL PLUTONIUM CORES

Density of Pu in core, gm/cm^3	Reflector			Critical Mass, kg Pu	Ref.
	Composition	Density, gm/cm^3	Thick., cm		
15.44	—	—	—	16.28[a]	18
15.54	Nat. U	18.8	24.1	5.73[b]	18
15.8	Nat. U	18.8	5.0	8.06	19
15.8	Nat. U	18.8	2.0	10.68	19
15.8	Beryllium	1.86	5.0	7.48	19
15.8	Beryllium	1.86	2.0	10.35	19
15.8	Carbon	1.63	5.0	10.05	19
15.8	Carbon	1.63	2.0	12.75	19
19.25	Beryllium	1.84	5.22	5.43	20
19.25	Beryllium	1.84	32.0	2.47	20
19.25	Beryllium	1.84	21.0	3.22	20
19.25	Beryllium	1.84	13.0	3.93	20
19.25	Beryllium	1.84	8.17	4.66	20

[a]Jezebel Assembly
[b]Popsy Assembly

Table 7-7 — CRITICAL EXPERIMENTS WITH NATURAL URANIUM-REFLECTED SPHERICAL Pu^{240} CORES

Data from Ref. 17.

Spherical core radius, cm	2.73		
Core No.	I	II	III
Weight of materials, gm			
Pu	1615.45	1610.30	1611.19
Ni	10.89	11.76	14.10
Oy (93.2% U^{235})[a]	9521	9755	10618
Isotopic composition of Pu			
Pu^{239}	0.9756	0.9497	0.8047
Pu^{240}	0.0234	0.0473	0.161
Pu^{241}	0.0010	0.0030	0.0292
Pu^{242}	—	—	0.0051
Spherical radius of natural uranium[b] reflector, cm		24.1	

[a]Density ≈ 18.75 gm/cm^3
[b]Density = 18.8 gm/cm^3

Table 7-8 — OBSERVED CRITICAL CONFIGURATIONS SPHERICAL CORES OF U^{233} AND Pu^{239} IN VARIOUS SPHERICAL REFLECTORS

Data from Ref. 21.

Core					Critical Reflector Thickness,[a] cm			
Material	Diameter, cm	Mass, kg	Density, gm/cm^3	Enrichment, wt-%	Enriched Uranium	Natural Uranium	Be	Tungsten Alloy
U^{233}	9 200	7.601	18.62	98.25	1 981	5 309	4 196	5 791
U^{233}	10 089	10.012	18.62	98.25	1 214	2 301	2 045	2.438
Pu^{239}	10 084	8 386	15.62[b]	b	1.656	4 128	3.688	4 699

[a]Reflector Densities, gm/cm^3
Enriched Uranium (93%) = 18.8
Natural Uranium 18.92
Be (98 wt-%) = 1.83
W-Alloy (91.3 wt-% W) - 17.21
[b]Density is for Pu This contains 4 9 at-% Pu^{240}, and 0.31 at-% Pu^{241}.

Table 7-9 summarizes critical experiments with unreflected plutonium cores. The plutonium is diluted with varying amounts of depleted uranium, steel, thorium, aluminum, and air.

Table 7-9 — OBSERVED CRITICAL MASSES UNREFLECTED PLUTONIUM CORES

Data from Ref. 22.

Diluent	Nominal Pu/Diluent Ratio	Average Density, gm/cm^3			Cylindrical Critical Mass, kg Pu	Critical L/D Ratio	Est Spherical Critical Mass, kg Pu
		Pu	Diluent	Ni			
None	—	14 27	—	0.651	21 39	0.546	17.5
Depleted U	2 1	9.83	5.97	0.448	27.3	0 955	24.7
Steel	2 1	9.78	2.50	0.446	32.8	1.23	28.6
Thorium	2 1	9.78	3.62	0.446	35 2	1.32	30.1
Aluminum	2 1	9.69	0.83	0.441	37.0	1.40	31.1
Air	2 1	9.98	—	0.455	77 1	2.82	43 7

Tables 7-10 and 7-11 describe plutonium core configurations in thick, natural uranium, and thorium reflectors, respectively. The range of core dilution with fertile and structural materials is larger than for unreflected cores since a limited supply of fissionable material could be better utilized due to the effectiveness of the reflectors.

Data in Tables 7-9, 7-10, and 7-11, are as reported. The diluted cores are quite heterogeneous and this must be recognized when contemplating a comparison between theory and experiment. Corrections for heterogeneity (Section 7.2.3) must be applied for precise comparison.

Table 7-10—OBSERVED CRITICAL MASSES NATURAL URANIUM REFLECTED[a] PLUTONIUM CORES

Data from Ref. 22.

Diluent	Nominal Pu/Diluent Ratio	Average Density, gm/cm^3			Cylindrical Critical Mass, kg Pu	Critical L/D Ratio	Est Spherical Critical Mass kg Pu
		Pu	Diluent	Ni			
None	—	14 23	—	0.652	8.96	0.23	6 8
Depleted U	2 1	9.77	5.94	0.447	10 35	0.387	8 8
	1 1	7.44	9.05	0.339	11.96	0 588	11 0
	1 2	5 06	12.27	0.231	16.91	1.22	15.5
	1 3	3.81	13.87	0.174	30.13	2.98	19.2
Steel	2 1	9.76	2.51	0.447	10.88	0.407	9.5
	1 1	7.45	3.80	0.339	13.55	0.664	12.7
	1 2	5.01	5.11	0.228	21.78	1.59	19.3
Thorium	2 1	9.76	3.63	0.447	11.13	0.417	9.9
	1 1	7.51	5.57	0.343	14.25	0.694	13.7
	1 2	5.07	7.49	0.231	25.15	1.81	21.7
Aluminum	2 1	9.76	0.840	0.447	11.04	0.414	9.9
	1 1	7.50	1.28	0.342	13.70	0.667	13.2
	1 2	5.05	1.75	0.230	22.36	1.62	20.2
Air	2 1	9.92	—	0.453	11.25	0.414	10.4
	1 1	7.62	—	0.348	14.58	0.70	14.6
	1 2	5.12	—	0.233	24.85	1.77	24 9

[a]Reflector thickness = 19 cm, reflector density ≈ 18.9 gm/cm^3

Table 7-11—OBSERVED CRITICAL MASSES THORIUM REFLECTED[a] PLUTONIUM CORES

Data from Ref. 22.

Diluent	Nominal Pu/Diluent Ratio	Average Density, gm/cm^3			Cylindrical Critical Mass, kg Pu	Critical L/D Ratio	Est Spherical Critical Mass, kg Pu
		Pu	Diluent	Ni			
None	—	14 5	—	0.659	12.75	0 322	9.7
Depleted U	2 1	9 91	5 99	0.451	14.65	0.541	12 5
	1 1	7 42	9 04	0.339	17.56	0.865	16 2
	1 2	5 06	12.27	0.231	30.78	2.222	21.3
Steel	2 1	9 76	2 50	0.446	16 02	0.60	14 1
	1 1	7 43	3.80	0 339	21.55	1 061	20 6
Thorium	2 1	9 82	3 63	0.447	16 61	0.618	15 1
	1 1	7 45	5 52	0 340	23 16	1 136	21 3
Aluminum	2 1	9 95	0 851	0 453	16 45	0 604	15 0
	1 1	7 59	1 30	0 346	22 80	1 098	21 2
Air	2 1	9 95	—	0 453	17 35	0 638	16 5
	1 1	7 65	—	0 349	25 75	1.23	24 5

[a]Reflector thickness 19 cm reflector density ≈ 11 3 gm cm^3

Table 7-12 describes critical experiments performed with high-density uranium systems. The core alloy is highly enriched uranium. The Godiva assembly is a spherical, unreflected system. Topsy is reflected with a natural uranium blanket, and has a much lower critical mass than Godiva. Uranium hydride cores with natural uranium and nickel reflectors are also given.

Table 7-12—OBSERVED CRITICAL MASSES: SPHERICAL URANIUM CORES HIGHLY ENRICHED IN U^{235}

Enrich., %	Density of Core Alloy, gm/cm^3	Reflector			Critical Mass, kg U^{235}	Ref.
		Composition	Density, gm/cm^3	Thick., cm		
93.9	18.75[a]	—	—	—	48.8	10, 23
94.1	18.75[b]	Nat. U	18.8	20.32	16.28	10, 23
93.5	18.75	Nat. U	18.8	5.08	23.75	23, 25
93.5	18.75	Nat. U	18.8	4.75	24.5	23, 25
93.9	18.55	Graphite	1.69	43.2	16.9	24, 25
93.9	18.55	Water	1.0	∞	23.2	24, 25
93.9	18.55	Paraffin	0.89	∞	22.2	24, 25
93.15	7.40[c]	Nat. U	19.0	20.32	12.61	24
93.15	7.40[c]	Nickel	8.8	20.32	12.63	24

[a]Godiva; [b]Topsy; [c]Hydride core ($UH_{2.97}C_{1.11}O_{0.25}$).

Table 7-13 summarizes the effectiveness of various reflectors around a spherical, enriched uranium core. Such data are basic to nuclear safety analyses. They can be very useful toward the determination of high-energy constants of these reflector materials in multigroup analyses.

Table 7-13—CRITICAL MASSES OF ENRICHED URANIUM SPHERES IN VARIOUS REFLECTORS[a]

(in kg enriched uranium; mass of U^{235} = 93.5 × cited values)

Reflector	Reflector[b] Density, gm/cm^3	Reflector Thickness			
		2.54 cm	5.08 cm	10.16 cm	∞
Be	1.84	29.2 kg	20.8 kg	14.1 kg	—
BeO	2.69	—	21.3	15.5	~8.9 kg
WC	14.7	—	21.3	16.5	~16.0
U	19.0	30.8	23.5	18.4	16.1
W-alloy[c]	17.4	31.2	24.1	19.4	—
Paraffin	0.91	32.6	—	—	21.8
H_2O	—	—	~24.0	22.9	22.8
D_2O	—	—	(27)	21.0	~13.6
Cu	8.88	32.4	25.4	20.7	—
Ni	8.88	33.0	25.7	(21.5)	~19.6
Al_2O_3	2.76	35.1	—	—	—
Graphite[d]	1.69	35.5	29.5	24.2	~16.7
Fe	7.87	36.0	29.3	25.3	23.2
Zn	7.04	—	29.8	25.0	—
Th	11.48	—	33.3	—	—
Al	2.70	39.3	(35.5)	(32)	<30.0
Ti	4.50	39.7	—	—	—
Mg	1.77	41.0	—	—	—

[a]Data from Refs. 25 and 26.
[b]Density of enriched uranium = 18.8 gm/cm^3.
[c]About 92 wt-% W.
[d]CS-312

NOTE: Parentheses indicate interpolated data.